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Organic semiconductors for visible light communications

Pavlos P. Manousiadis, Kou Yoshida, Graham A. Turnbull, and Ifor D. W. Samuel

Organic Semiconductor Centre, SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS, UK,
PPM, 0000-0001-8678-9126; KY, 0000-0002-9995-6525; GAT, 0000-0002-2132-7091; IDWS, 0000-0001-7821-7208

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Summary

Organic semiconductors are an important class of optoelectronic material that are widely studied because of the scope for tuning their properties by tuning their chemical structure, and simple fabrication to make flexible films and devices. Although most effort has focussed on developing displays and lighting from these materials, their distinctive properties also make them of interest for visible light communications (VLC). This article explains how their properties makes them suitable for VLC and reviews the main uses that have been explored. On the transmitter side, record white VLC communication has been achieved by using organic semiconductors as colour converters, whilst direct modulation of organic light-emitting diodes is also possible and could be of interest for display to display communication. On the receiver side, organic solar cells can be used to harvest power and data simultaneously, and fluorescent antennas enable fast and sensitive receivers with large field of view.

Introduction

Organic semiconductors are a special type of plastic materials with unique electronic and optical properties. They are particularly interesting because they combine novel semiconducting optical and electrical properties with simple fabrication and tuning of properties associated with organic materials. The electrical and optical properties of organic semiconductors are mainly due to their chemical structure so they do not need to be highly ordered crystals, in contrast to inorganic semiconductors. This makes their device fabrication simple – for example by deposition from solution – and is expected to translate into reduced cost of the final devices. In addition it enables side-by-side fabrication of different devices, such as red, green and blue organic light-emitting diodes (OLEDs) in a mobile phone display or television.

The optical and electrical properties of organic semiconductors are a result of their chemical structure, which consists of alternating single and double bonds between adjacent carbon atoms, known as conjugation. This leads to overlap of electronic orbitals and electron delocalisation (figure 1a). In conjugated molecules, the carbon atoms are sp^2-hybridised. Three of the four valence electrons are in orbitals in the plane of the molecule which form σ-bonds which hold the molecule together. The fourth valence electron is located in a p orbital extending above and below the plane of the molecule. Overlap between the $2p_z$ orbitals results in the formation of π-bonds and (when there are many atoms) π and π* bands. Electrons are delocalised along the molecule, and it turns out that there are two such electrons per repeat unit, leading to a filled band and semiconducting electrical and optical properties. This means that they can be used to make a range of semiconducting devices including light emitting diodes, solar cells, transistor and lasers. The commonly used organic semiconductor materials come from three groups: small molecules, polymers, and dendrimers[1, 2]. Many are soluble and so enable very simple deposition from solution; others are deposited by evaporation to make thin films for devices.

*Author for correspondence Ifor D. W. Samuel (idws@st-andrews.ac.uk;
and Graham A. Turnbull (gat@st-andrews.ac.uk).

A new field in which organic semiconductors are finding multiple applications is visible light communications. Although light has been used for communication since ancient times, it is over the past 30 years that optical fibres have come to dominate communications, and much more recently that strong interest in free space visible light communication has developed [3]. Also, known as Li-Fi (short for light fidelity) [4], light has many attractive features for data communications, including: i) 100s of THz license-free bandwidth; ii) simple front-end devices; iii) no interference with sensitive electronic equipment; iv) possibility for integration into the existing lighting infrastructure [5-7].

There are four main categories of devices based on organic semiconductors in VLC applications: colour converters, OLEDs, photo detectors (including both organic photovoltaics (OPVs) and organic photodiodes (OPDs)), and optical antennas. These devices use the distinctive properties of organic semiconductors in various ways. For example, the extensive electron delocalisation leads to very strong absorption and consequently a high radiative rate for emission. This leads to a fast on-off-on response when used for colour converters and optical antennas. Meanwhile the scope to tune the energy gap by adjusting the chemical structure is useful for optimising the absorption of OPVs and OPDs, and the emission of OLEDs.

Organic semiconductors as colour converters in VLC applications

One of the visions of visible light communication (VLC) is to use light fittings both for illumination and communication simultaneously [8, 9]. Solid-state lighting technology is already an established approach to provide good quality and cheap lighting. Blue-emitting GaN/InGaN LEDs coated with wavelength-converting phosphors are used as white light sources [10-12]. The role of the phosphor is to absorb part of the blue emission of the LED and convert it into yellow emission, resulting in white light (see figure 2a). Although phosphors are very suitable for generating white light from LEDs, their long luminescence lifetime (~microseconds) leads to a slow response that is a well-known bottle-neck for VLC applications [6, 13] (see figure 2b). Some early publications in white-light VLC used a yellow filter to filter out the slow phosphor emission to speed-up the data transmission [14]. The disadvantage of this approach is that only a portion of the illumination power is used for the data communication, thus limiting the signal-to-noise ratio (SNR) and the achievable data rate. A faster colour converter would be preferable, and there are a number of publications [15-17] where various alternatives to phosphors are investigated in order to tune emission and avoid rare-earth materials.

To be an effective colour converter for VLC, there are several criteria which a candidate material should satisfy. Firstly the material should be suitable for illumination: i) it should absorb in the region of 450 nm to match the nitride LEDs used for lighting; ii) it should have high photoluminescence quantum yield (PLQY), which is the number of photons emitted per photon absorbed; iii) the emission should be in the yellow region of the visible spectrum so that the combination of its emission with residual blue light from the LED results in white light; iv) the emission spectrum should be sufficiently broad to achieve good quality of illumination, which is measured by the colour rendering index (CRI). In addition, specifically for the VLC application, v) the time response of the materials should be fast (<10 ns, preferably < 1 ns) and comparable to the response of the other components of the data link. Simultaneously satisfying all of the above criteria is rather complex and demanding. Thus, the search for an appropriate material is also challenging, although there are candidates (see below). We note that for wavelength-division multiplexing (WDM) VLC scenarios, where multiple light sources of different colours are used, the criteria iii) and iv) would be adapted to the combination of emitters used giving good colour rendering.

Taking account of the above considerations, in 2014 Chun et al.[13] demonstrated an approach for white-light VLC in which the phosphor was replaced by an organic semiconductor colour converters. The simultaneous requirement for short emission lifetime and high PLQY means that high radiative rate is needed, which as mentioned earlier is a distinctive property of highly conjugated materials. Accordingly, the authors used the commercially available conjugated polymer “super-yellow” (SY) to generate white light from an inorganic micro-LED. The fast time response of SY (see figure 2c) enabled a bandwidth of more than 200 MHz to be achieved. This bandwidth was limited by the other components of the system and importantly was achieved without spectral filtering at the receiver. Even though, an illumination level of only 240 lx was achieved, partially due to low output power of the µLED used, they reported a 1.68 Gbps data rate. This was a record for white light VLC link at the time of publication, and demonstrated the feasibility of using fast fluorescent colour converters to enhance data rate.

The above work has been followed by further reports exploring organic semiconductors as colour converters for VLC applications. Sajjad et al. [18, 19] showed that blends of two organic polymers can be used as fast colour converters. This provides a convenient way of tuning colour by controlling the proportion of the polymer and the thickness of the film. Any CIE coordinate in the InGaN LED/polymer 1/polymer 2 is achievable, while the quality of the white light is high (i.e. high value of CRI), due to combined emission of the polymers. In this work, one polymer is excited and partially transfers its energy to another, by a process known as Förster resonance energy transfer (FRET) which takes place on a picosecond timescale. This is interesting because the energy transfer process is an additional decay pathway for excitations, and so speeds up the fluorescence of the initially excited polymer. For example, in publication [18] it was demonstrated that the lifetime of the BBEHP-PPV (τ=0.83 nsec), when blended with MEH-PPV (τ=0.38 nsec), can be reduced to 0.27 nsec. This allowed the team to achieve high bandwidth (>200 MHz), good CRI and data rates (>350 Mbps).

Other publications have explored specially-synthesized organic and polymer materials as colour converters for VLC. Vithanage et al. [20] studied star-shaped molecules that have a BODIPY core with different lengths of side arm. They demonstrated that Y-BODIPY molecules (figure 2d) with 3 fluorene units per arm (Y-B3) achieve the highest bandwidth of 73 MHz and also the best data rates of 370 Mbps. The time-resolved fluorescence of this material is shown in figure 2c. The fluorescence decay of Y-B3 is much faster than a typical phosphor (CL-827) or a II-VI quantum dot, but the conjugated polymers are faster still, making them more attractive. BBEHP-PPV has an exceptionally fast fluorescence decay, but is a green emitting material. A new conjugated polymer, BBEHBO-PPV, was therefore developed to have red-shifted emission. It retained the poly(2,5-dialkoxy-*p*-phenylene vinylene) backbone with bulky substituents of BBEHP–PPV, but attached the side groups via an alkoxy bridge (as applied in MEH–PPV) [21]. Due to its extremely short fluorescence lifetime (0.37 nsec), the material showed a high bandwidth of 470 MHz, while achieving a data rate of 550 Mbps [21] with on-off keying.

Other VLC colour convertor research has included routes to enhance the behaviour of organic semiconductors with metamaterials [22] and the use of perovskite nanoparticles [23]. In [22], Yang et al. took advantage of the Purcell effect by using nanopatterned hyperbolic metamaterials to enhance the radiative rate of an organic semiconductor colour converter. Specifically, the authors achieved to increase in bandwidth of the super-yellow polymer by 67 % without compromising the strength of the emission. Practically, this allowed an increase in the transmitted data rate from 150 Mbps, with bandwidth of 75 MHz, for planar super yellow films, to 250 Mbps, with bandwidth of 125 MHz, for the nanopatterned system. Mei et al. [23] have studied perovskite quantum dots, as colour converters. They used a yellow-emitting $CsPbBr_{1.8}I_{1.2}$ quantum dots and demonstrated a bandwidth of 73 MHz and data rate of 300 Mbps.

Organic semiconductors are an attractive alternative to inorganic phosphors as colour converters for blue-emitting LEDs. Their advantage is primarily due to their fast time response, with the additional benefit of being able to tune the light emission for bespoke lighting solutions. Their short emission lifetime (sub-nsec to few nsec), overcomes the bottle-neck due to the slow response (μsec range) of traditional phosphors. Organic semiconductors have considerable potential as colour converters in lighting, not only because they can implement more efficient white light VLC links, but also because they can provide high quality light cheaply, and without dependence on the rare earth elements in inorganic phosphors.

Organic light emitting diodes as light sources for VLC

Organic semiconductors can be used to make a range of semiconducting devices including organic light emitting diodes (OLEDs), solar cells and transistors. An OLED consists of one or more organic semiconductors layers sandwiched between suitable contacts. When a voltage is applied, it emits light. Whilst electroluminescence in a single crystal of anthracene was reported by Martin Pope and co-workers as early as 1963 [17], practical thin film OLEDs are generally attributed to Tang and van Slyke [24] and Burroughes et al [25]. OLEDs were initially developed for display applications and are now used in many commercial mobile phone displays and some televisions. Due to their unique fabrication and emission characteristics they are now also being developed for lighting, smart devices and wearables [26-29]. The progress made, means that it is now possible to apply OLEDs as transmitters for VLC and this has become an active area of research in recent years [30, 31].

The working principle of an OLED with the simplest structure is shown in figure 3a-c: an organic semiconductor light emitting layer is placed between two contacts. One of the contacts needs to be transparent, so indium tin oxide (ITO) is commonly used, and its high work function makes it suitable to be the anode i.e. to inject holes into the organic layer. The other electrode (cathode) is a metal and injects electrons into the organic layer. The injected holes and electrons move across the organic layer under the applied electric field, and charge pairs bind to form excitons (figure 3b). The exciton can then decay radiatively, and some of the light escapes from the device through the transparent contact. The efficiency of this simple structure is usually low due to unbalanced injection and transport of electrons and holes. Modern OLEDs therefore usually include additional layers to control charge injection, transport and recombination and so obtain much higher efficiency (figure 3d). The introduction of additional layers for injection of holes and electrons solves the problem of imbalanced carriers, by lowering the energy gap for injection from the electrodes [24, 25, 32]. Additionally, hole and electron transport layers can prevent the carriers from escaping the emissive layer without recombination. A more complete description of the principles of OLED operation can be found in: [32-34].

As mentioned earlier, the interest in OLEDs lies in their simple fabrication, emission characteristics, and the scope to be flexible and integrated into other objects. Many OLED materials can be deposited from solution, whilst others are thermally evaporated. This eliminates the need for high temperature epitaxial growth, and makes possible simple patterning of different colours side by side, and reductions in the overall cost of fabrication [35, 36]. The fabrication process of OLEDs enables the use of flexible substrates and so curved monitors and wearable electronics can be realised [26-29, 37]. Finally, there is a nearly unlimited number of chemical compounds which can be used as the emissive layer in OLEDs, making it possible to design and tune properties such as emission colour and colour quality [32].

Interest in the possible use of OLEDs as transmitters for VLC has only recently emerged. They are not obvious candidates for communication because the low mobility of organic semiconductors, and the high capacitance of these very thin devices, normally leads to a very low bandwidth. Typical charge mobilities reported for OLEDs are many orders of magnitude lower (10^{-3}–10^{-5} cm^2/ Vs) than for the inorganic materials used in LEDs (~ 1000 cm^2/ Vs) [38, 39]. This is partially mitigated in OLEDs by devices being much thinner (tens to hundreds nm). However, this thin device architecture leads to high values of capacitance especially for large OLED pixels (> mm^2) and consequently drastically limits their bandwidth [30, 39].

One of the first reports where an OLED was used as a VLC transmitter is by Minh et al. in 2011 [40]. They reported a data rate of 2.15 Mbps and a bandwidth of 150 kHz. One strategy followed by the authors was to apply an effective equalisation to minimise the effect of the high capacitance of the OLED. This enabled a VLC link to operate at several Mbps despite the large OLED surface area (3x4 cm^2, Lumiblade OLED by Philips) and resulting high capacitance of the device (~0.3 μF). As a result, the authors improved the achievable bandwidth of the device size and demonstrated a bandwidth of 1 MHz. The same group also reported VLC using another commercial OLED (Osram ORBEOS CMW-031) [41]. They followed the same strategy of achieving a better performance though equalisation, and reported a data rate nine times higher than without equalisation, reaching 550 kbps.

In 2013 the same group published a number of papers, setting a new record for VLC data transfer using OLEDs, investigating different modulation schemes. In [42], Haigh et al. used a spectrally efficient modulation scheme (discrete multiton – DMT) and achieved a data rate of 1.4 Mbps, 14 times the bandwidth of the system used . In [43], they achieved a data rate of 2.7 Mbps and demonstrated online filtering for the first time. This early progress established OLEDs as feasible transmitters for VLC, and this has become an active area of research [30, 31].

The growth of the reported data rates is shown in figure 4. A new landmark was reached in 2014 [44, 45], when a data rate of 10 Mbps was reached. In the same year the data rate record was further doubled [46] by using a custom-made OLED. The fasted reported data rates were 27.9 Mbps in 2015, [47] and reached 51.6 Mbps in 2017 [48].

VLC using OLEDs is a fast growing field. The interest in OLEDs is due to their distinctive characteristics compared to inorganic LEDs, including flexible devices, scalable fabrication of different emitting colours side-by-side, tunability, and low cost of production. Despite the limited bandwidth of OLEDs, researchers have demonstrated rapid improvement in the data rates obtained.

Organic photodiodes and photovoltaics as receivers for VLC

A frequently occurring VLC scenario is where the receiver or the transmitter is a stand-alone device, with no direct access to the power grid. Examples of this scenario include monitoring sensors, mobile home appliances, and devices, such as mobile virtual assistants, domestic robots, and smartphones. One interesting approach to address the problem of powering these devices is to use photovoltaics as the powering source and as receivers for VLC signal. The idea is that the solar cell will have a dual functionality transforming the ambient and the light for communication into electrical power for powering the stand-alone device [49].

The principle of organic photovoltaics (OPVs) is illustrated in figure 5. The basic structure of an OPV is similar to that of OLEDs – with organic semiconductor layer(s) in between conductive contacts, one of which is transparent (figure 5a). Light is absorbed by the organic materials, and as a result a bound electron-hole pair i.e. an exciton is created (figure 5b). The excitons diffuse to an interface between donor and acceptor materials (or regions of the sample), and the charges are separated by the difference in energy levels between the materials (figure 5c). Finally, the separated charges are extracted at the contacts. In many modern OPVs, the donor and acceptor materials are mixed together to form a so-called bulk heterojunction, while additional layers allow the transport of the desired charges but block the opposite charges from reaching the "wrong" contact (figure 5d).
The first reports of using organic photodiodes as VLC detectors were published in 2013. Arredondo et al. [50] investigated whether organic bulk heterojunction OPVs based on P3HT:PCBM can be used as photodetectors in VLC. They reverse biased the OPV and demonstrated a modulation bandwidth of 790 kHz. We note that "reverse biased" means that the OPV acts as a photodiode and does not generate power. In [51], Colado et al. demonstrated an all-organic flexible VLC system. In this study, flexible OPVs were manufactured in a roll-to-roll process and used as a receiver for VLC. They also operated the OPV in reverse bias to improve the bandwidth up to 200 kHz. The aim of the report was to show the possibility of a VLC link made entirely from organic components, and the authors demonstrated audio data transmission.

A more innovative way to use the OPV came in 2015 by Zhang et al [52]. In this report, the authors did not reverse bias the OPV but adapted a receiver circuit (see figure 6) to harvest the energy from lighting while simultaneously receiving communication data. The energy harvesting and data communication branches of the receiver circuit were low and high frequency filters, allowing the simultaneous dual functionality of the OPV. The authors found that this configuration could simultaneously harvest 0.43 mW of power (5.4 mW/cm^2) and receive data at a rate of 34.2 Mbps. When the receiver was optimised for data transmission the data rate reached 42.3 Mbps.

The field of OPVs as detectors for VLC is rather new with few reports to date. Despite the relatively low bandwidths and data rates reported so far, they offer the exciting possibility of c cheap and self-powered solutions for VLC receivers, and so have great potential for future VLC implementations.

Fluorescent antennas for VLC

One challenge for VLC is to have receivers that are both sensitive (high SNR) and fast (high bandwidth) (see figure 7a). A small photodetector is fast but not sensitive, i.e. has a high bandwidth but provides low SNR (see figure 7b). A large photodiode is sensitive, but slow, i.e. has high SNR but low bandwidth (see figure 7c). A lens, or another optical element such as a compound parabolic concentrator, can mitigate this by collecting the light over a large area and concentrating it onto a smaller area. Thus, it can increase the SNR of a small photodetector (see figure 7d). For these reasons, most VLC systems rely on short focal length optics to focus the light onto fast photodiode receivers toachieve the required SNR and bandwidth for high speed communications. However, this configuration leads to a need for careful alignment to the source (see figure 7d), which is not practical for applications where the receivers are mobile (e.g., a laptop or a smartphone). A recent series of publications has demonstrated an alternative approach, using photonic devices based on fluoresce and total internal reflection, can overcome this limitation and achieve a significant gain with a wide field-of-view.

Due to a fundamental principle in optics, the conservation of étendue [53, 54], for any optical system based on refraction and reflection there will be a trade-off between the optical gain (the output power density, S_{out}, divided by the input power density, S_{in}) and the field-of-view of the system (Ω_{in}) (see figure 8a) [55-57]. In practical terms, this means that the more gain an optical system can provide, the more limited is its field-of-view (see figure 8b). As a result, while VLC systems based on optical elements can achieve high SNR due to the high optical gain, they usually have a very limited field-of-view.

In 2014, Collins et al. theoretically showed that a fluorescent antenna, a device similar to a luminescent solar concentrator [58-60], could be used in VLC to overcome the limitations for optical systems set by the conservation of étendue [61]. Such devices could provide similar gain to conventional optical systems, while maintaining a wide field-of-view. In 2016, the experimental demonstration of this concept followed was made by two independent groups [62, 63]. The principle of these devices is illustrated in figure 8c: The incident light is absorbed in a layer of fluorescent material, and then re-emitted as fluorescence. Most of the emitted light is trapped in the layer by total internal reflection and propagates within the device to the edge of the antenna. Due to the much smaller cross section of the edge of the device than the absorbing area, significant optical gain can be achieved, while the field-of-view follows the cosine law. The experimental result shown in figure 8d demonstrates that these devices can provide much wider field-of-view when compared with lenses with similar optical gains (see figure 8d). This is a consequence of the fact that the angle of emitted light is independent from the angle of incident light, and the conservation of étendue between the incident and the emitted light does not apply.

The two experimental publications [62, 63], followed rather different approaches for implementation of the fluorescent antennas. Manousiadis et al. [62] demonstrated devices with a slab geometry, while Peyronel et al. [63] used optical fibres to construct fluorescent antennas. In [62] the device was fabricated by sandwiching a mixture of epoxy with a fluorescent dye between two microscope slides. The authors demonstrated an optical gain of 12, with full width at half maximum field-of-view of 120°, while the bandwidth of the devices was 40 MHz, significantly higher than that of most commercially available LEDs designed for illumination, which typically are in the range of 5-20 MHz [64, 65], and achieved a data rate of 190 Mbps, limited by the receiver used. In [63], the authors used a bundle of commercial fluorescent fibres aligned in a planar array. They demonstrated an optical gain of 12.3, with a bandwidth of 91 MHz, achieving a data rate of 2.36 Gbps. Interestingly, the authors demonstrated a concept of an omnidirectional antenna made out of fluorescent fibres. The importance of this is that it solves one of the bottlenecks in the practical mobile detector VLC application, since the signal can be detected at any incident angle.

Other authors have looked into whether nanostructures can be used to enhance the performance of fluorescent antennas. Dong et al. [66] used a nano-patterned fluorescent antenna to influence the direction of light propagation. They used a parabolic shaped fluorescent antenna with a specifically designed bottom layer with a nano-patterned diffraction grating. They showed experimentally that this nano-patterned approach improved the optical gain of the antenna from 2.2 to 3.2. Wang et al. [67] reported that arrays of metallic nanoparticles can act as étendue reducers. They have shown that an aluminum nanoparticle array can interact with dye molecules, suspended in a polymer, and change the angle distribution of the emission. Specifically, the emission is mostly confined into an 8° cone at the back side of the nanoparticle array. As a result, the emission can be more readily focused onto a detector. Their key reported finding was that the étendue of the emission is smaller than that of the incident light.

Other functionalities to the fluorescent antennas have recently been reported. Mulyawan et al. have shown that fluorescent antennas can be used to implement a multiple-input and multiple-output (MIMO) scheme for VLC [68]. A Fresnel lens was used to project two light sources transmitting data onto a very optically dense (high concentration of absorbing material) fluorescent antenna. Due to attenuation of the fluorescence propagating through the device, the authors could reconstruct the initial information sent by the two channels from detectors attached to two different edges of the antenna. In a recent publication [69], Rae et al., demonstrated a VLC transceiver which has both receiving and transmitting capabilities. Their device was based on a fluorescent antenna with a transfer-printed micro-LED attached. As a result, this device not only could receive (downlink) VLC signals via the fluorescent antenna, but could also simultaneously transmit (uplink) through the micro-LED. Beside this dual functionality, this device could also operate in an optical relay mode, with the interesting possibility to establish a VLC connection between a transmitter and receiver which are not in direct line-of-sight.

Fluorescent antennas constitute a new and a very promising approach to overcome the key limitation of link alignment in VLC applications. The motivation for their initial introduction was to provide an optical antenna which could provide usable gain, without limiting the field-of-view of the receiver to few degrees. Since their theoretical introduction, there have been a number of publications achieving impressive results in terms of both data rate and novel functionality.

Conclusions and future perspectives

This article has reviewed recent developments of various organic semiconductor devices for application in VLC. In the future, we can expect to see continued performance improvements in each type of device. We can also anticipate further advances that make full use of the distinctive properties of organic semiconductors, notably including their scope for flexibility and the opportunity to integrate many devices side by side. This is particularly relevant to future implementations supporting the internet-of-things (IoT).

The concept of IoT is the extension of internet connectivity into everyday objects. This will allow things to communicate with each other for automation, and be remotely monitored and controlled [70-74]. VLC can provide solutions for fast, interference free, and secure communication for IoT, leading to a world of interconnected devices, smart homes, environmental monitoring, and display-to-display or even car-to-car communications. However, to realise the full potential of IoT with stand-alone objects, there remains a major obstacle. In many IoT scenarios numerous sensors are required which cannot be connected to the electrical grid, but must have power autonomy. These sensors must be powered both to undertake their sensing function and for transmitting and receiving data. The exciting development by Haas et al. to demonstrate simultaneous power and data harvesting in inorganic solar cells [49] may help solve this challenge. As mentioned above, this approach is also possible with organic solar cells, which would be particularly suitable for integration into smart sensors. The spectral response of OPVs is better matched to indoor lighting than silicon [75], making OPV a highly compelling technology for indoor energy harvesting.

The tremendous recent developments in manufacturing OLED televisions and smartphone mean it should be possible to make complex arrays of OLEDs or OPVs dedicated to VLC. These could provide a platform for spatial and wavelength multiplexing, multiplying currently achievable data rates. Another development associated with the production process of organic devices, is the integration of different devices either side-by-side [69], or devices that have dual functionality [52]. This could lead to a new generation of low-cost, purpose-built devices for VLC applications [76]. Overall, we see a bright future for organic devices in VLC application, and Gbps communication may not be too far away.

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FIGURES

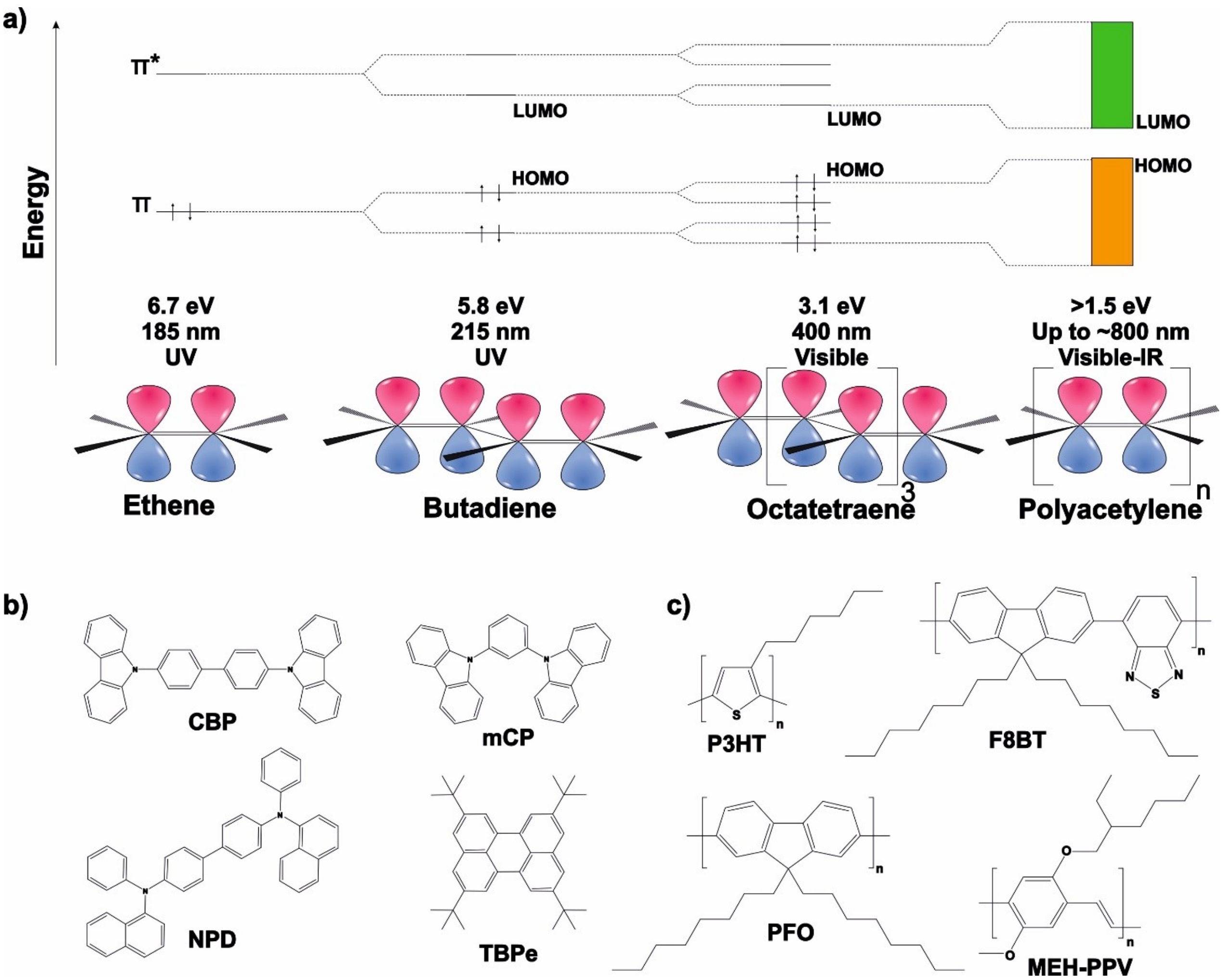

Figure 1. (*a*) Schematic representation of energy levels in alkenes as a function of conjugation length. With increasing conjugation length, the energy gap between the HOMO and LUMO decreases, resulting in absorption and emission at longer wavelengths. (b) Chemical structures of several commonly used small molecule organic semiconductors for OLEDs. (c) Chemical structures of several commonly used organic semiconductor polymers.

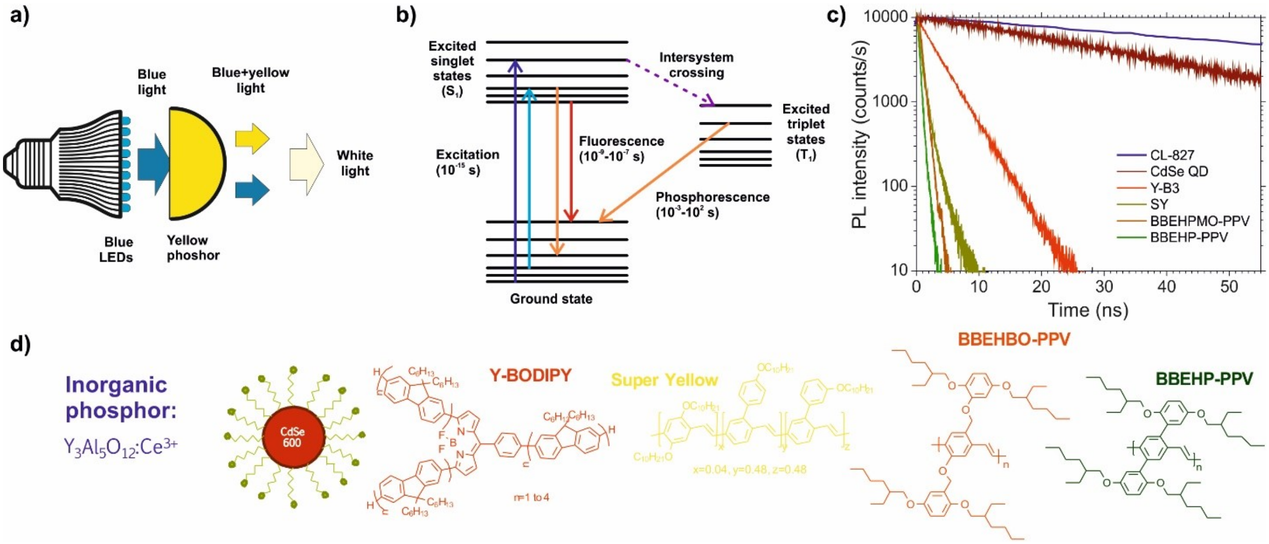

Figure 2. (*a*) Basic principle of a white LED based on a phosphor colour converter. The electroluminescence from a blue LED is partially absorbed by a phosphor colour converter. The phosphor emits the absorbed energy as yellow light. The mixture of blue and yellow light results in white light. (b) Energy diagram of fluorescence and phosphorescence processes in an organic molecule. A photon excites an electron to a higher energy level, leading to the formation of a bound electron-hole pair, or exciton, on the molecule. The exciton is formed in a singlet spin configuration (S_1) The exciton can relax from S_1 to the ground state with the emission of a photon (fluorescence) fast processes (10^{-9}-10^{-7} s). The singlet can also relax non-radiatively to the ground state, or intersystem cross to an excited triplet state (T_1). The transition from T_1 to ground state (known as phosphorescence) has low probability, resulting in a much slower decay time (10^{-3}-10^{2} s). (c) A comparison plot of the time response for various colour converter materials: a commercial YAG yellow phosphor (CL-827), a CdSe quantum dot, a custom-synthesised BODIPY molecule with oligofluorene arms (Y-BODIPY), the commercial fluorescent polymer "super yellow" (SY), and two custom-synthesised fluorescent polymers (BBEHP-PPV [18] and BBEHBO-PPV [19]). (d) Chemical structure of the various materials presented in (c).

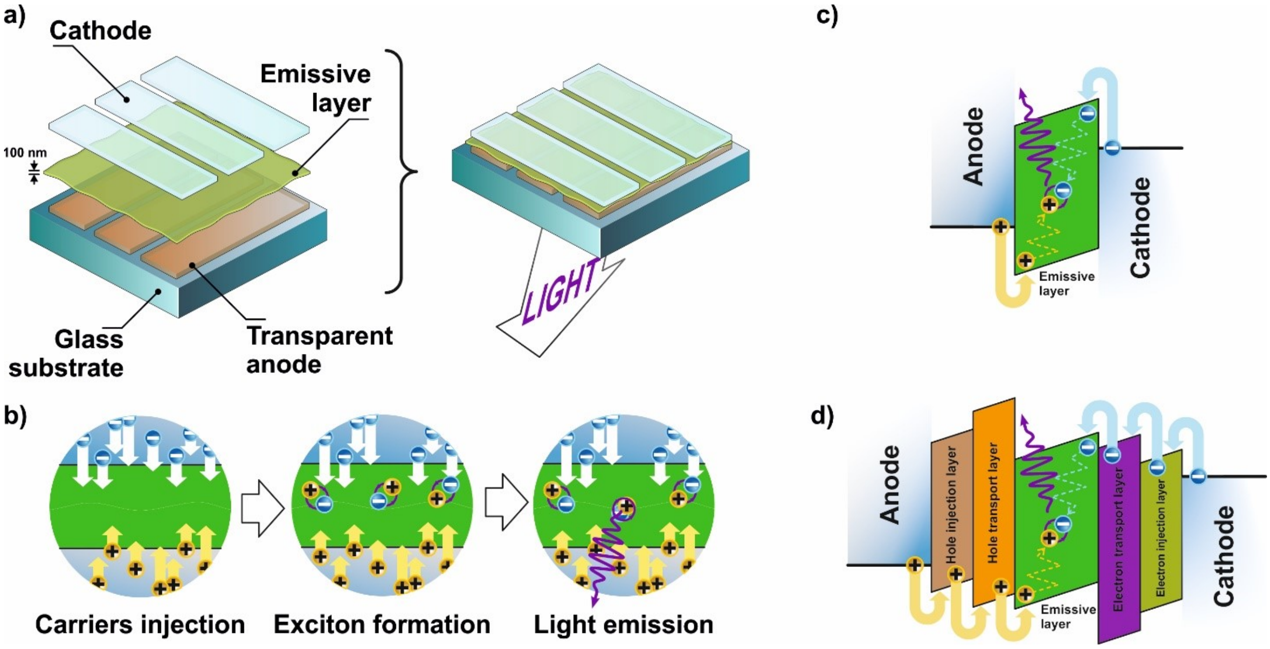

Figure 3.
Basic principle of OLED operation. (a) Structure of single-layer-OLED. (b) Mechanism of OLED operation: carrier injection from contacts, formation of exciton by holes and electrons, and light emission from an exciton. c) Energy diagram of single-layer-OLED. d) Energy diagram of modern multi-layered-OLED.

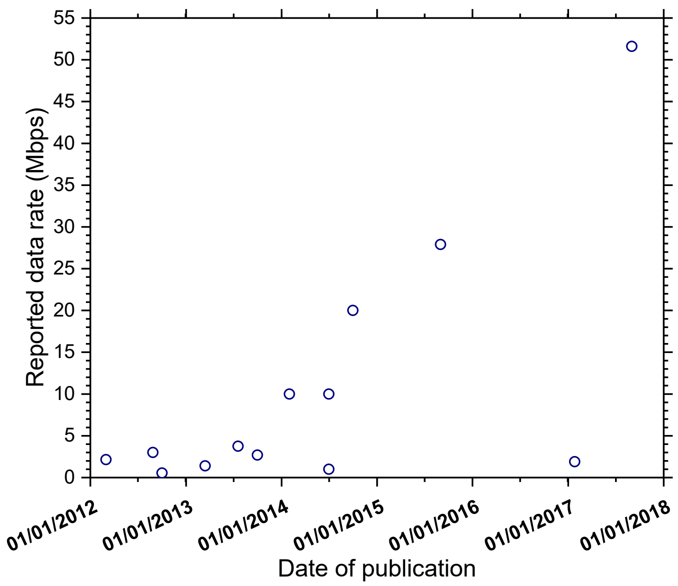

Figure 4.
Reported VLC data rates using OLED devices as function of publication date.

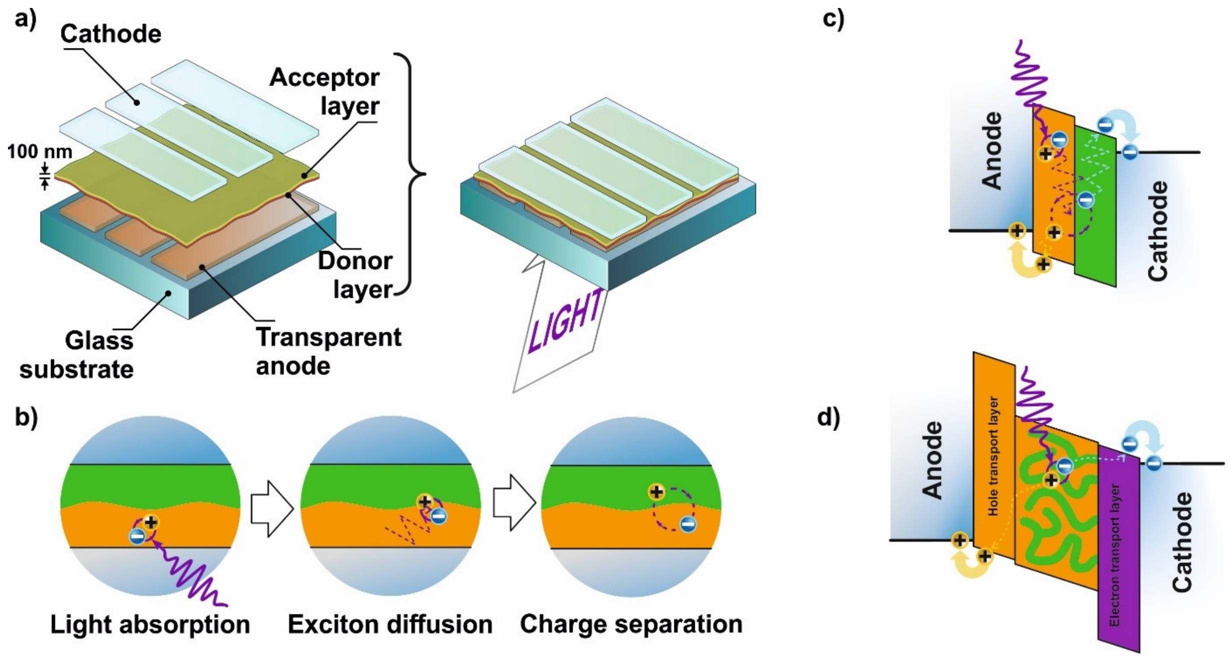

Figure 5.
Basic principle of operation of an organic photovoltaic cell. (a) Structure of a bilayer OPV device. (b) Mechanism of OPV operation: photons are absorbed by the donor layer and create excitons. The excitons diffuse to the heterojunction interface with the acceptor and are dissociated into holes and electors. c) Energy diagram of dual layer OPVs. d) Energy diagram of modern multilayer bulk heterojunction OPV.

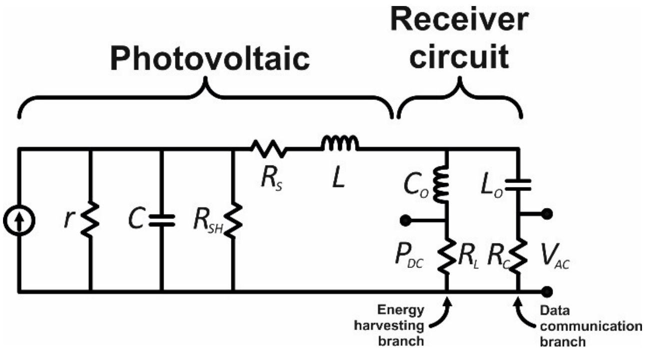

Figure 6.
Equivalent electric circuit of a solar cell (left part) and receiver circuit (right part) from [52]. The receiver circuit has two branches, which separates the received current into DC and AC components. The DC component is used for energy harvesting, while the AC component for data communication.

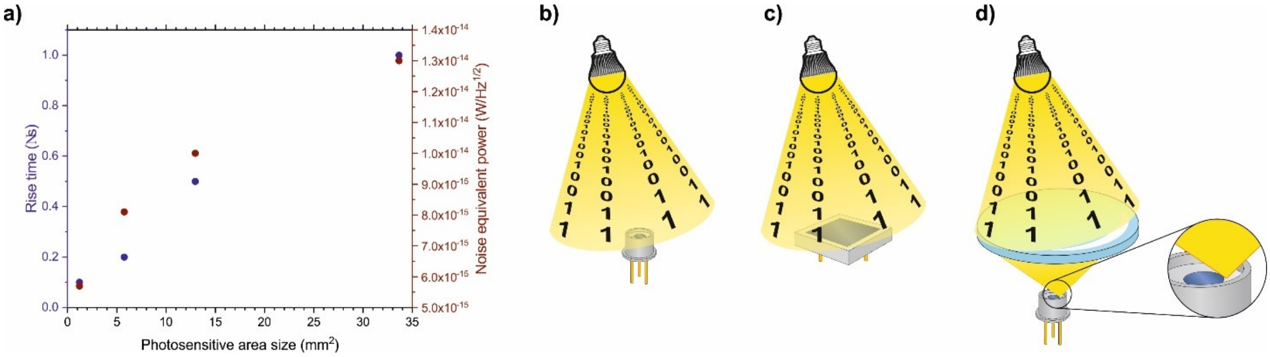

Figure 7.
(a) Plot of rise time and noise equivalent power as function of photosensitive area of silicon photodiodes. The plot is based on values provided by the manufacturer [77]. (b) If a small photodiode is used in aVLC link it can provide high bandwidth but low SNR. (c) If a large photodiode is used in the VLC link, it can provide high SNR but low bandwidth. (d) A lens can combine a large collection area with small photodiode and achieve high SNR with high bandwidth, but precise alignment to the source light is crucial.

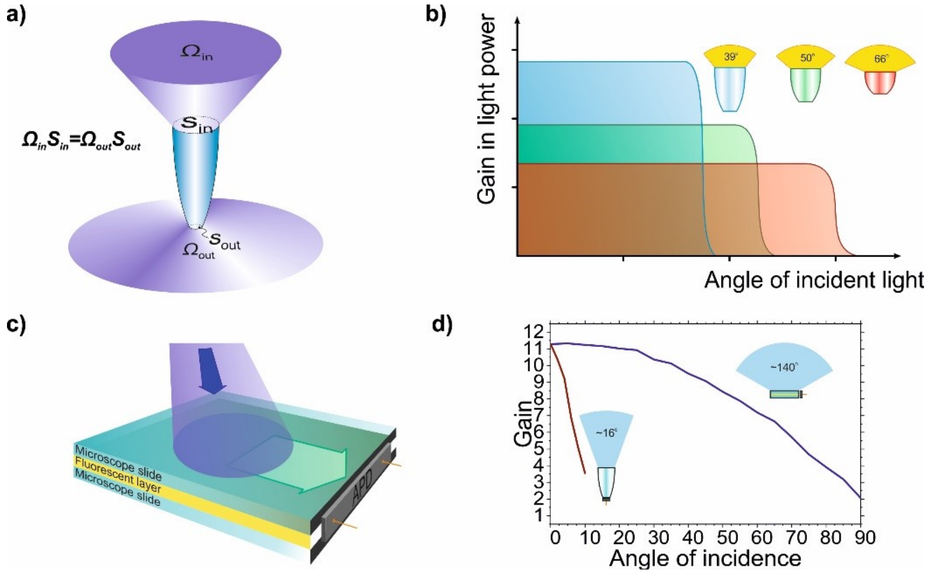

Figure 8.
(a) Conservation of étendue. (b) Graphical comparison of gain and field of view for three compound parabolic concentrators. (c) Basic principle of a fluorescent antenna. (d) Experimental comparison between gain vs angle for a florescent antenna and a concentrating lens. A fluorescent antenna has field-of-view (full width at half maximum) of ~2 x 70°, while a lens of similar gain has field-of-view of about 2 x 8°.

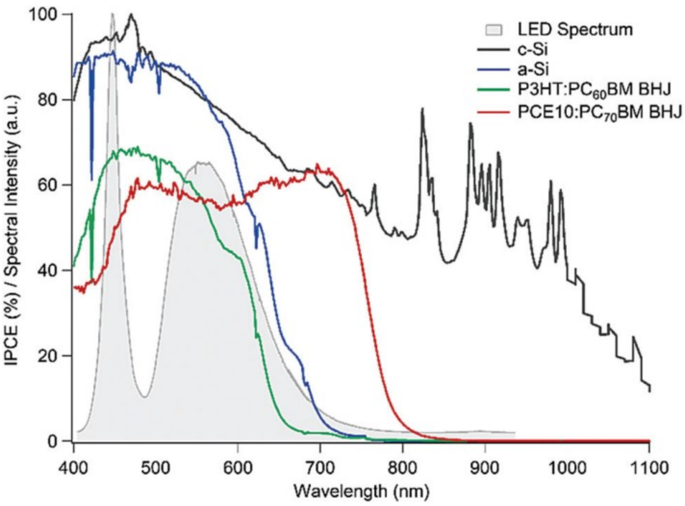

Figure 9.
Incident photon-to-electron conversion efficiency for the following devices: crystalline silicon (c-Si), amorphous silicon (a-Si), P3HT:PC60BM bulk heterojunction (P3HT:PC60BM BHJ), and PCE10:PC70BM bulk heterojunction (PCE10:PC70BM BHJ) devices. Also shown is the emission spectrum of a commercial white LED light. Reproduced with permission. [75] Copyright 2016, The Royal Society of Chemistry